Methods And Systems Using Prediction Of Outcome For Launched Objects

This invention relates to methods and systems using prediction of outcome for launched objects.

According to one aspect of the present invention there is provided a method for deriving representations of the individual outcomes of launching objects into an area that contains a plurality of mutually-spaced object-sensing means, wherein each sensing means detects the presence of any of the launched objects that arrive in the location of that respective sensing means, a prediction of the outcome of the launching of each individual object is computed in dependence upon measurements of velocity vectors of that object at launch, the prediction is used to provide representation of the outcome of the launch of that respective object in the event that the presence as aforesaid of that object is not detected by the sensing means, and the computation process by which the predictions are computed is subject to adaptive correction in dependence upon error between the outcome predicted and the actual outcome realised in respect of individual objects for which the presence as aforesaid is detected by any of the sensing means.

According to another aspect of the invention there is provided a system for deriving representations of the individual outcomes of launching objects into a defined area, comprising a plurality of mutually-spaced object-sensing means within the defined area, each of the sensing means being operative to detect the presence of any of the launched objects that arrive in the location of that respective sensing means, launch-analyser means for deriving measurements of the launch velocity vectors of each of the objects individually, computer means for

computing in dependence upon these measurements a prediction for the respective object of the outcome of its launch, and means for providing representation of the computed prediction in the event that the presence as aforesaid of the respective object is not detected by the sensing means, and wherein the computation process by which the predictions are computed by the computer means is subject to adaptive correction in dependence upon error between the outcome predicted and the actual outcome realised in respect of individual objects for which the presence as aforesaid is detected by any of the sensing means.

With the method and system of the invention, the representation provided in respect of the individual objects for which the presence as aforesaid is detected by any of the sensing means, may be the actual outcome realised.

The method and system of the invention is especially applicable to providing representations of the outcome of successive strikes of a golf ball, for example in the context of a golf range. In this respect, measurements of the launch velocity and spin vectors of a ball can be used to predict its ensuing flight-carry and -duration, its landing speed, landing backspin, angle of descent and subsequent bounce and roll. However, the accuracy of such prediction is very prone to errors arising from inaccuracies in the flight model, the bounce and roll model and the launch measurements and also variations in atmospheric conditions (e.g. wind speed, rain, temperature and pressure) and also in the rebound and friction properties of the landing terrain. The method and system of the present invention enable a significant improvement in prediction accuracy to be achieved by sensing the actual outcomes realised in relation to some shots and from the way in which these differ from the

predicted outcomes computed for those same shots, correct the computation process adaptively to reduce error.

The "end-of-flight" parameters may be predicted and measured, namely, the carry-length, the direction and the flight duration. One possible means of achieving the measurement of actual carry distance and deviation and the flight duration is disclosed in WO-A-9201494 which describes the use of geophones distributed around a reception area to sense the impact of the ball as it lands. Signals corresponding to the time of arrival of the impact vibration at proximate geophones are recorded and, by analysing the time differences in these signals at different geophones, the position and time of impact can be accurately measured.

As an alternative, passive or active radio-frequency identification ("RFID") tags may be embedded in each golf ball and used for identifying the final position of the ball. A system that employs passive RFID tags to locate the final positions of golf balls is described in US-B-6,607,123. In the present case, balls may be first identified at the tee and then at instrumented target areas on the driving range outfield where means is provided to interrogate the tags, dependent on ball position. This in turn provides data on the final outcomes of a proportion of golf shots and such measurements may be used to correct the ball launch calibration parameters and the prediction of ball carry, bounce and roll, taking into account prevailing atmospheric conditions and prevailing bounce and roll characteristics of the terrain.

The measurement of velocity vectors and/or other parameters of a launched ball or other object may be carried out for the method and system of the present invention by detecting light-change resulting from

passage of that object through detection planes defined by respective slit-apertures. Each detection plane may involve means for emitting light as a beam through the respective slit-aperture and means for sensing light from the beam reflected back through that same slit-aperture from the object. The angle subtended at the object by the light-emitting means and the light-sensing means is preferably less than 3 degrees, in these circumstances. More particularly, the subtended angle (identified as the "observation angle") is preferably less than 1 degree, and more desirably less than 0.5 degree or even 0.2 degree.

The light-emitting means and its co-acting light sensing means (referred to collectively as a "TXRX pair") preferably operate in the infrared or near-infrared spectrum as this suppresses interference from extraneous daylight sources and is invisible to the user; however, other light wavelengths may be used. Furthermore, the light emitted may be continuous or pulsed. For example, low duty-cycle pulsed emissions with a repetition frequency in the range 10 kHz to 100 kHz may be used with measurements coinciding with each pulse. This corresponds to providing measurements of club-head and ball positions at intervals of a few millimetres to a fraction of a millimetre. (In a 'full swing' golf shot the club head speed at impact is typically in the range 25 metres per second to 55 metres per seconds, and ball launch speeds are typically 30% to 60% greater). For applications where the movement of a golf putter is to be measured, the repetition frequency can be much lower (e.g. about 1 kHz).

The light emission may be square-wave or sinusoidal modulated or the like, with high modulation frequency (e.g. 50 to 100 kHz or higher), and the received signal highly amplified and narrow-band filtered (preferably

with a phase sensitive detector) so that very weak signals from retro-reflectors can be detected. This embodiment can be arranged to read identifying codes, such as dot-codes, on more slowly moving objects and/or on larger retro-reflectors with long-range and large capture-window applications.

A detection plane may be established as indicated above by arranging the active elements in a TXRX pair in close proximity (e.g. 2 to 10 millimetres apart, but not limited to this range) and some distance behind a slit-aperture. The width of the slit-aperture may nominally equal the distance between the emitting means and the light-sensing means in the TXRX pair ("the TXRX separation"), with the length axis of the aperture perpendicular to the axis that is co-linear with the centre of the light emitting means and the centre of the light-sensing means in the TXRX pair ("the TXRX axis"). Neglecting the finite size of the active areas in the TXRX pair and diffraction effects at the edges of the aperture, the width of the detection plane in this arrangement is nearly constant throughout the useful extent of the detection plane and is equal to the TXRX separation (typically 3 to 4 millimetres). This controlled-width detection plane is advantageously used in conjunction with retro-reflectors that have much greater reflective efficiency than diffuse reflectors, with the efficiency increasing with smaller observation angles. This increased efficiency helps to compensate for spreading losses at increasing range (and thus decreasing observation angle). When the detection plane is not more than x millimetres in width (where x can be any number, but typically 3 to 4 millimetres), different features in the shape or pattern of the reflector can be detected provided that these features are separated by at least x millimetres. By providing a line array of light emitters and light sensors with adjacent elements in the

array forming a TXRX pair and with the array axis normal to the length axis of the slit-aperture, the position of the detection plane can be altered, depending on which TXRX pair is selected or made active. In this arrangement, each TXRX axis is co-linear with the array axis.

Another way of creating a detection plane is to arrange that the TXRX axis is parallel to the length axis of the slit-aperture. Provided the TXRX separation is small compared to the length of the slit-aperture, the fields of view for the light emitting means and light-sensing means are nearly identical. The detection plane thus formed comprises the common field of view. An advantage of this type of detection plane compared with that previously described, is that more light is emitted into the detection plane and more light is reflected back from the detection plane because the entire field of view is used. However, the width of the detection plane increases with range as it spreads out into a wedge shaped volume. This can be corrected using a cylindrical lens, so that the detection plane is again of uniform thickness (equal to the width of the slit-aperture) or nearly so. This method of forming the detection plane improves its sensitivity and operating range.

It is sometimes desirable to use a diffuse reflector (e.g. one side of the surface of a golf ball). Because diffuse reflection is inefficient, the method of creating detection planes described in the immediately-previous paragraph is preferred for diffuse reflection. In this case it is sometimes advantageous to have larger TXRX separation (giving greater observation angles) to suppress retro-reflection relative to diffuse or spectral reflection from the golf ball or other object.

The golf ball or other object may carry one or more reflectors. A single reflector comprising an area of reflective surface of distinctive shape, such as a triangle or rectangle, may be used. Alternatively, two or more separate reflective surfaces may be used in a defined pattern, such as circular dots arranged along a line, a barcode pattern, or three dots on the corners of a triangle. Although diffuse reflection may be used, there are advantages to be achieved using retro-reflective elements. These later elements are preferably, but not necessarily, of the corner-cube or prism type, and may be provided with special prism structures with biased and/or variable tilt axes in order to orientate the maximum reflectivity at an incidence angle other than 90 degrees, and/or to make the reflectivity more uniform over a range of incidence angles. In the case of a golf ball, it may have just one retro-reflector with the remainder of the ball surface providing a diffuse reflector, but preferably it carries a plurality of retro-reflective dots arranged in a spherically symmetric orientation on the ball. The golf club used may also carry at least one retro-reflector preferably on the club-head and/or on the lower end of the shaft, above the club-head.

Means may be provided to enhance the detection of a retro-reflector in the presence of unwanted reflections from other parts of the moving article by placing a first light polarizing filter in front of the light emitter and a second light polarizing filter in front of the co-acting light sensor. Light reflected from the retro-reflector has its plane of polarization rotated 90 degrees (or theoretically so). The two filters are oriented so that the planes of polarization are at 90 degrees to one another (or at optimum cross orientation), so only the polarized target-reflected light is allowed to pass through the said second polarizing filter and

into the light sensor. When the polarized emitted light strikes other (non-retro-reflective) surfaces of the object being detected or internal surfaces in the measurement apparatus, its plane of polarization is not rotated, and the returned beam is blocked from entering the sensor. A second co-acting light sensor may be provided on the obverse side of the light emitter with a polarized filter aligned with the plane of polarisation of the emitted light. This is insensitive to reflected light from retro-reflective surfaces but sensitive to other reflective surfaces, and provides two signals, for example, one responsive to retro-reflective dots on the surface of a golf ball and the second responsive to reflections from the ball surface alone.

Various types of polarizing filters may be used such as Rochon, Brewster or dichroic polarizers. One type of dichroic polarizer that is advantageously useful at infrared wavelengths is the wire-grid polarizer. Wire-grid polarizers are very expensive to manufacture compared to the much more common sheet polarizers (based on modified polyvinyl alcohol iodine) but, in the present context, the dimensions of the filters are exceptionally small so it is economic to use wire-grids. Since both the emitter and sensor devices in a TXRX pair share a common focusing lens and/or slit-aperture, the filters are preferably fabricated on or very close to the active areas of these devices. The active areas are very small (e.g. 0.1 to 1.0 square millimetres) so the polarizing filters are also very small. Judicious design of the wire-grids and associated conductors can also help to reduce radio frequency interference in the sensor signals generated by the relatively high power emitter drive signals. Anticipating future developments in light emitter and sensor devices, the emitter and/or sensor may transmit/respond in one plane of polarization without need of additional filters.

Preferred shapes for the reflectors have simple geometries such as circular, hemi-spherical (i.e. a golf ball surface), triangular or quadrilateral. However, any shape that can be defined mathematically may be used. In one preferred embodiment, the shape comprises one or more small circular dots having diameters of similar sizes as the width of a detection plane and arranged in known relative positions on a golf club, golf ball or other object to be measured. The detection planes are preferably arranged to traverse the path of a reflector at various positions along the path and at various angles thereto. As a reflector travels through the various detection planes, data capture circuits record the corresponding time and amplitude response. These data are used to compute the speed, position and direction of the reflector and thus determine the ball and/or club head motion. A powerful technique for extracting accurate three-dimensional data of the motion of a reflector as it passes through an array of detection planes is the Levenberg-Marquardt method for non-linear estimation. This, and alternative estimation algorithms, require a fairly representative mathematical model of the measurement system and to this end it is advantageous that the reflectors have basic geometries that can be described in simple mathematical terms.

The object-sensing means, which may for example utilise optical, acoustic, electromagnetic, electro-mechanical, or radio-frequency sensing, may be utilised in the context of golf shots for example, to detect the outcome of the ball flight (i.e. the carry distance and deviation and the duration of flight), or of the entire travel of the ball to where it comes to rest. The vibration created by the impact of the ball on landing may be detected, and data derived from the position and time of impact for a proportion of balls may be utilised with data comprising the carry distance, deviation and

duration of flight, to correct the ball launch calibration parameters and/or the ball flight model parameters. Optionally, the position and/or timing of a second impact of a ball (i.e. after bouncing off the ground) may be measured to determine the final direction, descent speed and other end-of-flight parameters.

The vibration sensing means may be single devices, each attached, for example, to an individual panel that vibrates on impact so as to indicate the landing of a ball on the panel, and/or may involve a distributed array of geophones to sense ground transmitted vibrations or the like. One preferred geophone arrangement uses buried piezoelectric cables near the perimeter of a sensing zone and/or arranged along grid lines distributed across the sensing zone.

Methods and systems in accordance with the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a logic block diagram of a system according to the invention for use in providing a golf-range facility;

Figure 2 is a flowchart showing the main computation and decision routines used in the system of Figure 1;

Figures 3(a) and 3(b) illustrate two scenarios of actual and predicted golf shots;

Figure 4 is a diagrammatic plan view of the outfield of the driving-range facility;

Figures 5(a) and 5(b) are a plan view and a sectional side view of a short-range target of the driving-range facility of Figure 4;

Figures 6(a) and 6(b) are a plan view and a sectional side view of a distance-range target of the driving-range facility of Figure 4;

Figure 7 is a flowchart showing main computation and decision routines used in the system of Figure 1 as an alternative to the computation and decision routines of Figure 2;

Figures 8(a) and 8(b) are a plan view and a sectional side view of an instrumented target that uses radio-frequency identification to detect balls on the target;

Figure 9(a) and 9(b) are schematic diagrams showing a launch analyser for use in the system of Figure 1, together with a golf ball prior to its launch;

Figure 10(a) and 10(b) are schematic views illustrating the establishment of detection planes corresponding to those of the launch analyser of Figures 9(a) and 9(b);

Figures 11(a) and 11(b) are diagrammatic plan and side views of a golf ball passing through detection planes corresponding to those of the launch analyser of Figures 9(a) and 9(b);

Figure 12 shows time-dependent waveforms representing sensor signals generated from the detection planes of Figures 11(a) and 11(b);

Figure 13 is a plan view of a launch analyser which is responsive to movement of the golf-club head as well as of the golf ball during launch of the ball, and which may be used as an alternative to the launch analyser of Figures 9(a) and 9(b) in the system of Figure 1;

Figure 14 is a side view illustrative of operation of the launch analyser of Figure 13; and

Figure 15 shows time-dependent amplitude waveforms generated illustrating signal responses generated from detection planes shown in Figure 14.

Reference axes X, Y and Z are shown for convenience in conveying orientation, where this is appropriate in certain of the figures to which reference is made in the following description. In this respect, the Z-axis is vertical and points upwards, the Y-axis is horizontal and points downrange (i.e. along the general line of flight of a golf shot), and the X-axis is orthogonal to the Y- and Z-axes and points in the general 'heel-to-toe' direction of a club head at ball address.

The block diagram of Figure 1 outlines the top level system for a golf range facility where several golfers hit golf balls into the same general area. Blocks representing first, second and Nth golfers using the range are show as 1, 2 and 3 respectively. The golfers launch golf balls downrange onto the outfield 4 at random times and with random distances and direction, and some of the balls land on instrumented targets 5. In a first version of the instrumented target, the "end of flight" or "end of carry" position and time of balls can be measured from vibrations caused by the balls hitting the surface of an instrumented target as they first land at high speed on the outfield, with means provided to locate the radiation centre of these vibrations and the point in time of their occurrence. In a second version of instrumented target, the "end of run" positions of balls can be measured using a passive or active RFID tag embedded in each ball to uniquely identify all balls in the driving range and means are provided in the instrumented targets to read tag identifying codes on any

ball that runs or bounces onto that target. If required, a driving range with the second version of instrumented targets can additionally be provided with ball landing impact sensors (similar to the sensors in the first version of instrumented target) to enhance the quality of data for actual shot outcomes. Preferably, all the golf balls used in the facility are of similar external construction with nominally equal weight and diameter (which is true by default for all standard golf balls), and of closely similar impact and aerodynamic properties, which again is easily achieved.

The golfers 1, 2 and 3 are provided with individual launch analysers 6, 7 and 8, and balls are dispensed to them at or near the tee, or at a central dispensing station. The launch analysers 6, 7 and 8 measure the initial speed, spin and launch angles of driven balls and from these measurements predict the flight or the flight and run of the balls. If balls with embedded RFID tags are used, the launch analysers also register a golfer- or user-code by means of a key- or card-reader. Each golfer is in this case issued with an individually-coded key or card for use in registering his/her code at the allotted launch analyser, and the same key or card is used for the allocation to him/her of RFID-tagged balls, so that the unique codes of all balls dispensed to the individual golfer can be identified with the launch analyser where they are to be used. Two or more golfers may share one key or card and select their name on a touch-screen or by other selection means when taking turn to play.

The data from the launch analysers at each driving bay are transmitted to a central computer 9. The computer 9 matches balls that are detected on any instrumented target with the golfer who hit that ball, and computes the error between the predicted outcome for that golfer's

shot (based on launch analyser measurements) and the actual outcome.

In one form of RFID tagged ball each ball is provided with an active RF transmitter, preferably using an internal re-chargeable power source. Typically, the power source may have capacity of a few milliamp-seconds or less (e.g. from charge stored in a high-value multi-layer ceramic capacitor or the like). The power source may be charged through a connector but preferably charge is provided from an inductively coupled external field prior to hitting the ball off the tee. The balls may be activated to transmit their unique code by an RF field that is local to each target area. The position of a stationary ball on a target area can then be sensed either by buried loops within operating range of the tag transponders or by directional scanning antennas located in the vicinity of each target area.

In one arrangement, the RFID reader at each target area is provided with a plurality of buried loops or antenna and receiver channels configured such that at least one can receive transmissions from the golf-ball active tag dependent on its orientation. The RFID tags may be programmed to be normally in standby (low-power mode) and momentarily power-up at two to three second intervals or other intervals so that if it is in radio range with at least one antenna/receiver circuit it can indicate its presence. The interrogation (i.e. radio communication between reader and tag) is then performed using the in-range channel. This means that only one channel performs the interrogation, and that transmit-power is required of the reader only when a ball first lands on a target area. Preferably, means may be provided on each tag to sense the high energy impact of the golf shot and initiate power-up only after impact and optionally shut down after

the tag code is successfully transmitted to the target area receiver.

In a second and preferred form of RFID tagged ball, the embedded RFID devices are passive. This requires that balls that roll or bounce onto an instrumented target subsequently roll back into a collecting channel or duct or the like where they come in close proximity to a RFID reader. Preferably, instrumented targets that sense passive RFID balls are fairly small in diameter or span compared with their individual distances from the driving bays. Thus a passive RFID type target at 100 metres range could be typically ten metres in diameter (if circular), which would then have a measurement resolution of ±5%; this assumes that there is only one passive RFID reader per target area. Numerous such targets would be provided on the outfield to ensure a reasonably high success rate of shots landing on targets. Although the resolution is only ±5% (or some other percentage), the system is still able to minimise systematic errors to nearly zero, since very large numbers of balls are sampled and the average of all measurements is sensitive to small systematic discrepancies.

Instrumented targets of either RFID mode are more akin to "real golf" than targets that detect impact, in that the equivalent to the target in real golf is the green with a hole and a flag and the aim on "approach shots" is to strike the ball so that it flies, bounces and finally rolls to a stop close to the flag - or better still, drops into the hole. With RFID instrumented targets, each target can be provided with a regulation size hole and a traditional flag. The target surface emulates the surface of a traditional green and the hole is provided with a RFID reader to register "hole-in-one" shots. The chances of achieving a hole-in-one on a driving range according to this embodiment of the invention are similar

to the chances of achieving a hole-in-one on a traditional golf course.

The instrumented target areas comprise a fraction of the total outfield area so a proportion of balls may land in intermediate areas between the target areas. In these instances, the outcome of a golf shot is interpolated using computer prediction of the outcome based on accurately measured ball launch parameters. The instrumented target measured data is used to apply corrections to the data generated in each of the launch analysers 6, 7 and 8 and to update the golf shot prediction model so that the interpolation of shot outcomes is accurate. The above corrections are generated using iterative algorithms that test where and how much correction is appropriate so after a few results from each launch analyser the predicted and actual data converge (to within very small tolerance). The correction process continues as long as golfers hit balls onto the instrumented target areas and adapts to environmental changes on an hour-to-hour and day-to-day basis. The computer can also monitor long-term calibration drift in each launch analyser and apply appropriate correction, or report that specific components of the facility require maintenance. A weather monitor 11 positioned downrange, measures wind speed and direction and air density and signals the results to the central computer to assist the prediction process. In consequence, each video display unit 12, 13 and 14 provides the relevant golfer with a reliable representation of great precision, of the outcome of each of his/her shots.

For one shot per bay, the average number **M** of balls detected within an instrumented range may be considerably less than the number of bays in use **N**. In a busy 50-bay driving range, about 6000 balls per hour are hit during

peak usage. It is only necessary to have a few hundred results per hour to obtain very good feedback for adaptive correction purposes. Thus, in a driving range according to the invention, it is only necessary to measure the actual outcome of a fraction of the total of driven balls in order to provide accurate prediction of all balls hit. Furthermore, because golfers have an incentive to land their balls on a target, the density (i.e. number per unit area) of balls landing on instrumented targets is relatively high compared with the density elsewhere, so the total area of instrumented targets dispersed around the outfield as a ratio of the overall area of the outfield is significantly less than the ratio **M/N**. Thus, in a driving range according to the present invention, the area occupied by all the instrumented targets as a percentage of the total available area of the outfield may be less than 10% or even less than 2%. This very low coverage of outfield sensors provides significant cost advantages compared with ranges where most of the outfield is populated with landing sensors or the like.

The launch analyser apparatus may be provided with a card-reader or other key device that may be mechanical or electronic. The code contained in such device can be used to provide membership account data, membership expiry date (if required) and credit amount for future playing time. In the case of a range using RFID tagged balls, the code contained in such device can be additionally used to identify which balls are dispensed to one or more players in each bay. Additional data such as a customer's e-mail address can be used to relay the results of a practice or game session directly to the customer's home PC. Alternatively, data from individual customers could be automatically posted on a website and each customer provided with a unique password to allow private access to their results.

Figure 2 is a flowchart showing the main computation and decision routines required for the system of Figure 1 when the adaptive correction is provided by impact vibration sensors that detect when and where balls land on the outfield. In Figure 2, the decision block 20 sorts the predicted data into two streams depending on whether the data has or has not an acceptable chance of hitting an instrumented target, where the acceptable chance is defined as the probability that the prediction is within six-sigma metres of a target (i.e. six-sigma metres from any landing sensor). This criterion gives a very high confidence that virtually all possible chances are included and obviously may be modified in practice to less than six-sigma metres if desired. The predicted results for shots expected to land out of range of any target are displayed without further processing (routine 27) and these typically form the majority of all golf shots in the driving range, whereas the remaining predictions are included as candidates for matching with balls that land on any of the landing sensors.

In routine 21, each ball detected by the landing sensors is assigned to the most probable prediction. The probability that a ball is correctly assigned to a given shot prediction can be calculated from the ratios of the errors in predicted carry length, carry deviation and flight duration to the respective standard deviations of errors in these three parameters. It is thus very desirable to frequently monitor and update the values of standard deviation in prediction errors and assign each prediction with the best current estimate of the applicable standard deviations. For example, standard deviations in the predicted outcome for short chip shots will be very small compared to those for a long drive. The chip shot is nearly unaffected by wind and ball spin, whereas the drive is very sensitive to these factors.

Occasionally golf shots will land on the same target nearly simultaneously, or will be predicted to do so. In these circumstances it is desirable to hold the incoming data (routine 22) until such time that any possible confusion between two actual shots is resolved. Decision routine 23 checks whether there is any confusion, that is, whether the process tries to assign two actual shots to one golfer. When this happens, a second predicted shot must exist so that for every two actual shots there are two predicted shots, but sometimes the allocation is wrong. In these circumstances, routine 24 computes the combined probability of both combinations in order to choose which is the most likely. That is the probability that A matches with B AND C matches with D is found and then the probability that A matches with D AND C matches with B is found and the combination with higher probability is chosen. The process can then be repeated and expanded if yet another ball lands at nearly the same time and in close proximity.

For the above process to be meaningful, it is important that reliable values of standard deviations in the various error parameters are obtained. Typical values for standard deviations in predicted carry distances and flight duration are published (see Quintavalla, S.J. 2002 "A generally Applicable Model for the Aerodynamic Behaviour of Golf Balls", In *Science and Golf IV*, ed. E. Thain, p. 346, London: Routledge). Values of 1.65 metres standard deviation in ball carry of 240 metres (average) and 100 milliseconds standard deviation in flight time (estimated to be about 7 seconds) were reported.

The timeout routine 25 stops the holding process (routine 22) when the probability of new (future) data from the landing sensors matching with held predictions becomes diminishingly small. For example, the standard

deviation of errors in flight time prediction for a certain type of shot may be 100 milliseconds. If such a predicted shot has a chance of hitting a landing sensor (detected in routine 20) it should be held until such time that the actual shot detected on the landing sensor is registered. But if this does not happen after six-sigma seconds (i.e. 600 milliseconds) there is negligible chance of it ever happening. The data that is released from the "hold" state is then checked in routine 26 to see whether it is actual and matched or only predicted. In the event that the released data is a predicted outcome that is not matched, it is displayed to the appropriate golfer via step 27. However, in the event that the released data is an actual outcome that has been matched to a prediction, this actual outcome is displayed to the golfer via step 28, and the error of the prediction from the actual, realised outcome is analysed in routine 29 for adaptive correction of the prediction process in the computer 9. Over a long period of time, thousands or even millions of matched results can be recorded and analysed to give adaptive correction. This will allow very sensitive control and detection of non-random errors. For example, fuzzy logic or other algorithms can be used to correlate changes in wind speed and direction with shot outcome and anticipate the corrections required.

Figures 3(a) and 3(b) illustrate two scenarios where ambiguity or confusion between shots occurs. In Figure 3(a) two actual shots 31, 32 and two corresponding predicted shots 33, 34 are shown where the errors in predicted carry length are much exaggerated. Actual shot 31 lands first at point A1 and since this is closer to P2, the predicted point landing of shot 32, the process will first match A1 with P2 instead of P1. However, a few milliseconds later, actual shot 32 lands at point A2 and the process will then assign A2 to P2 and thus the

prediction P2 is assigned to both A1 and A2. The process must then select a second prediction (P1) and it will find that the probability of A2 being matched to P1 is very small indeed and will reject this in favour of the correct assignments, namely A1 to P1 and A2 to P2.

The carry errors illustrated in Figure 3(a) are typical of those produced by a gust of head wind, where the carry lengths of both shots are reduced. In general, errors in the same direction will not cause the system to finally match predicted and actual shots incorrectly. A second error scenario is illustrated in Figure 3(b) where the predicted shots 35 and 36 have large errors in opposite directions with P2 being predicted to be much shorter than A2 and P1 predicted to be much longer than A1. In this case the system will fail to finally match actual and predicted correctly. This scenario could arise if two launch analysers are used simultaneously to measure very similar shots on the same target and one analyser "reads high", while the other "reads low". This occurrence will be very rare and is limited to instances where two balls land very close together, at nearly the same time and significant length or line prediction errors in opposite directions cause the predictions to "cross over".

The predicted carry length, deviation and duration may be found using the following equations:

$$dv_x/dt = -Bv(C_D v_x + C_L v_y \sin\alpha) \quad (1)$$

$$dv_y/dt = -Bv[C_D v_y - C_L(v_x \sin\alpha - v_z \cos\alpha)] \quad (2)$$

$$dv_z/dt = -g - Bv(C_D v_z - C_L v_y \cos\alpha) \quad (3)$$

where; $B = \rho A/2m$

g is the acceleration due to gravity

ρ is the density of air

m and A are the mass and cross-sectional area of a golf ball

Equations 1 to 3 are a simplified form of the trajectory equations for a golf ball, assuming that the ball spins about an axis in the XZ plane at angle α to the horizontal, i.e. it does not have "rifling spin". When α is zero, the ball has no sidespin but only backspin. If required, additional terms to account for rifling spin can be added, but in practice these make very little difference to the predictions.

The trajectory equations give the rate of change of the three vector components v_x, v_y and v_z of the trajectory velocity v of the ball after impact, so knowing the initial velocity vectors (i.e. the velocities in the X, Y and Z directions) and other parameters in the equations, the flight path and duration can be calculated. C_D and C_L are the applicable drag and lift coefficients, which are dependent on the ball dimple pattern and the linear and angular velocity of the ball relative to the surrounding air. These dependencies are in general highly non-linear and difficult to predict analytically for all possible golf shots. However, according to the present invention, the adaptive correction process allows the system to learn fairly precisely how C_D and C_L vary under virtually all possible golf shot conditions and also adapt to changes in environment such as air pressure, and temperature (which affect ρ). Thus, after an initial learning period, the prediction of shots becomes very accurate and the remaining errors are predominantly random with very small standard deviations, or due to changes in ambient conditions. It should be realised that the bulk of the said learning period is a "once off" occurrence. That is, once a first system has been built and commissioned, the initial learning process for one type of ball and one type of launch analyser will be the

same for the same type of ball and launch analyser in other sites.

The flight prediction yields information on the landing velocity and final backspin rate of a ball. After initial touch-down, a ball typically bounces a few times and then rolls to a halt. The duration and length of the bounce and roll phase can be estimated approximately with appropriate formulae involving the ball landing data and bounce and roll coefficients for the landing surface. Again, feedback of actual results (e.g. from known outcomes of RFID tagged balls) allow the system to learn accurate relationships between ball landing parameters and subsequent bounce and roll behaviour across the entire outfield.

Figure 4 is a diagrammatic plan view of the outfield, purely exemplary of a driving range according to the invention with tee-off bays (not shown) disposed along curved line 40. Five distance targets 41 to 45 are distributed beyond a barrier 46 and a plurality of short range targets 47 are disposed between the barrier 46 and the tee line 40. Arrows 48 indicate the straight ahead aiming directions for the two bays at the ends of the tee line 40. The centres of all the distance targets 41 to 45 are arranged to be within ±20 degrees of the direction of the arrows 48 and are also within ±20 degrees of the straight-ahead direction of all other bays. The sum of distances from any one bay to all the five distance targets average out to about the same total by virtue of the curvature of the tee line 40. Thus, each bay provides approximately the same degree of difficulty to successfully hit all targets. One short range target 47 is provided for a small group of bays so that again the degree of difficulty to hit a short range target is approximately the same, irrespective of bay position.

The barrier 46 is an optional feature, which may extend across the outfield or part thereof at about 40 to 50 metres (or at other distances) from the tee-off bays. It may be 0.5 to 1.0 metres high (or higher) and may comprise separate, spaced apart barriers. Its purpose is to provide a simple and easy test for beginners or very young players that also may form part of a points-scoring game. For example, hitting the barrier "on the fly" (i.e. without the ball rolling or bouncing before reaching the barrier) may score one point, whereas balls that carry over and beyond the barrier score two points. Distributed vibration sensors, for example a piezoelectric cable, built into the barrier or barriers sense when it is hit by a ball and the launch analysers confirm the bay from which any successful shot is made. The barrier thus provides a test of initial ability to at least hit a ball off the ground and carry some distance down a fairway, but ability to hit straight is not required.

A second stage of ability is provided by the short range targets 47, which require some degree of both distance and direction control. These targets are typically set at 20 to 25 metres range and provide an attainable goal for the weakest players but also a facility for higher-ability golfers to practice their short game with precise feedback.

Figures 5 (a) and 5 (b) are a plan view and a sectional side view of a possible design for a short range target. The target 47 is typically circular in plan view, but may be otherwise shaped, and comprises a generally dome-shaped outer shell with a lid 50 and a skirt 51. The lid 50 attaches to the skirt 51 via a shock absorbent mounting 52 so that vibrations from impact on the skirt do not transmit readily to the top. The shell may be supported slightly above ground level by a shock

absorbing mounting 53, which may extend throughout the full perimeter of the lower lip of the skirt 51. A ball landing directly on the outer shell 50,51 creates an impact noise that is detected by a microphone 54 inside the shell. The microphone 54 may be designed to reject far-field noise and signal processing can be provided to distinguish between the sound of ball impact and other sounds such as wind, rain or thunder. A vibration sensor 55 attached to the lid 50 also senses impacts that land on the lid 50 but not on the skirt 51 and thus provides feedback to the central computer to distinguish between impacts on the skirt 51 and impacts on the lid 50. Once ball impact is detected, a processor 56 sends a signal to the central computer 9 (Figure 1) to indicate a successful shot and record the precise time of the impact. Balls that roll along the ground towards the target 47, hit the shock absorbing mounting 53, but such impact generates insufficient sound intensity for detection. It may be preferable to provide some degree of damping on the shell 50,51 to limit the amount of rebound and/or impact sound intensity.

Typically, the overall diameter of the target 47 is 10% to 20% of its distance from the tee line 40 so as to provide a fairly easy target. The lid 50 typically has a diameter of only 20% to 50% of the overall target diameter and is thus much more difficult to hit directly with a golf shot. Optionally, the shell 50,51 can be formed as one piece and a microphone used to detect impacts on any part of the shell (i.e. providing no distinction between impacts on the lid 50 and skirt 51). The slope of the skirt 51 should not be steeper than 45 degrees on any part facing the bays, since otherwise there is a danger of a very hard hit, low trajectory ball rebounding back towards the bays. Optionally, the central top part may be provided with a layer of high friction and/or softer material so that balls landing

with high backspin can be observed in the way they bounce upwards or backwards.

Preferably the ground surrounding a target 47 is fairly soft so that nearby missed shots do not rebound high off the ground and subsequently land on the target. However, on the rare occasions this does happen, the launch sensing and flight prediction system accurately distinguishes between direct hits and hits off a ground-bounce so that such shots are not rewarded a game score. It should be noted that for very short distance shots (up to 30 metres or so) the ball flight is almost purely ballistic and not significantly affected by aerodynamic effects due to ball spin and/or wind. This is because the aerodynamic lift and drag forces on a ball are proportional to the square of its absolute velocity through the air. This being the case, extremely accurate predictions of landing positions and landing times are obtained from the flight prediction system for short, low velocity shots. These predictions can be calculated very quickly, so that the result is computed before the ball finishes its flight of 1 to 2 seconds through the air.

To enhance the fun aspect of the driving range, visual and/or auditory feedback may be provided on the targets 47. For example, at least part of the shell may be fabricated from a material that is translucent but impact resistant, and a high intensity lamp 57 may be provided inside the shell to be switched on at the instant a validated shot hits the target. The light intensity can then be controlled to dim gradually, reducing to zero intensity over a few seconds, unless another ball hits the target in which case the transient light process is repeated. The intensity of the light can also be adjusted to be much greater during sunlight-conditions as compared with night-time or low-daylight conditions. This provides a golfer with highly visible and instant

feedback of success and in addition three points (say) can be added to his or her game score. In this regard, a message such as "3 POINTS!" can be reverse printed on the inside of the skirt 51 in an opaque colour that matches the colour of the shell 50,51, so that it is visible (as illustrated in Figure 5(a)) through the translucent skirt 51 as a dark symbol against an illuminated background, when the internal lamp 57 is switched on. Various other lighting and colour effects can be provided. Additionally or alternatively, the sound of a ball impacting a short range target may provide auditory feedback and optionally this can be amplified and relayed to a speaker system local to the bay from which the ball was launched. This latter option can be arranged so as to confine the auditory response principally to just the one appropriate bay.

Figures 6(a) and 6(b) show a plan view and a side sectional view of a distance range target typical of the targets 41 to 45. Here, the ground forming the target is contoured. The central and intermediate zones form a dome or hillock 60 with preferably a uniform slope from top to bottom to ensure that balls are not able to come to rest on the hillock 60 but instead roll down and into a trench 61. The outer zone of the target is sloped into a conical dish 62 so that again balls do not rest but instead roll into the trench 61. The trench is itself sloped so that balls rolling into the trench continue to roll (from left to right in the diagram of Figure 6(b)) and then down a drain pipe 63 and finally into a collection sump 64 from which they are periodically collected and returned to a washing and dispensing machine in the bay area. The floor of the trench 61 is preferably lined with a layer of low rolling friction material so that the balls roll easily down the trench and into the drain pipe 63, which has an internal surface with very low rolling friction. Similarly, the surface

of the target is preferably artificial turf with low rolling friction. By this means, only small gradients are required to ensure that balls continue rolling from any part of the target and into the sump 64. However, it is also preferable that any area on which a ball might land (i.e. the target surface or the trench floor) should also have low rebound coefficient so that most of the kinetic energy of the ball is absorbed on first impact on the target.

To enhance the visibility of the target, especially at night-time, the perimeter of the target is marked out with retro-reflective reflectors 65. These are arranged on an outer bank 66 with the reflectors 65 nearest the golfers (on the left-hand side in Figure 6(b) positioned near the bottom of the bank 66, and the reflectors 65 furthest from the golfers on the top, or even above, the bank 66. Thus, a circle of reflectors 65 is formed, which is slightly tilted up and towards the golfers so as to be in good view. A central flag and flag-pole 67 may also be retro-reflective. However, it may prove preferable to use high efficiency, coloured LEDs.

Two separate, concentric piezoelectric cables 68 are buried a few centimetres below the target surface and adjacent to the perimeter circle of reflectors 65. These cables 68 are connected to a differential amplifier (not shown) so that common-mode noise (i.e. noise from distant sources such as road traffic, wind, etc.) is rejected and only vibrations caused by impacts close to the cables 68 (e.g. golf-ball landing impacts) are sensed. This arrangement detects very precisely whether a ball lands inside or outside the perimeter circle. A second set of piezoelectric cables 69 are arranged in a grid formation covering the surface of the target inside the perimeter circle. Each of the cables 69 (of which only eight are shown) is connected to an individual amplifier (not

shown), and is preferably buried somewhat deeper than cables 68. The cables 69 detect balls landing on any part of the target inside the perimeter circle to provide measurements of landing position and landing time.

Preferably, a local signal conditioning and processing unit (not shown) is provided at each target 41 to 45. This analyses the raw data, rejects far-field impacts and computes the co-ordinates of the first (and optionally second) impact of balls landing within a given radius of the target centre. This processing unit will also communicate with the central computer 9 (Figure 1) and with any peripheral equipment. Power and communications lines may be provided by underground cables, but optionally cables will only be used to connect the target sub-system components. The powering of the sub-system, including of radio communications to the central computer, can be from rechargeable battery and/or a local solar power generator.

As with the short range targets 47 (Figure 4), it is desirable to provide optional special effects when golfers successfully hit the target to enhance the "fun" aspect of the facility. This can be limited to only a central zone of each distance target and may be provided with high pressure water jets to form transient fountains on each (fairly rare) occasion that a ball carries to a central zone. Each distance target 41 to 45 would be provided with one such water jet situated near the centre of the target and controlled to operate for a few seconds each time a ball lands on its central zone. Since the ball flight to distance targets is always a few seconds duration, the prediction that a ball will land may be computed before it actually does, so the response time (ball landing to jet operation) can be nearly instantaneous. To enable various other custom special effects, a general purpose control interface can be

provided. This would provide multiple triggering signals to operate such devices as balloon releases, display rockets or other fireworks or the like that would be operated/ignited in synchronism with balls landing near the centres of targets.

Other designs of target, which may include traditional landscaped greens, bunkers and water features, etc., may be provided instead of, or in addition to, the distance targets described above.

Figure 7 is a flowchart showing the main computation and decision routines required for the system of Figure 1 when the adaptive correction is provided by RFID readers that identify "captured" balls, that is to say, balls landing on outfield targets. The readers and central computer 9 identify each captured ball with the bay from which it was hit. The code for each individual ball as it is dispensed to the golfer (routine 70) and the system also identifies which golfer plays from which launch analyser. The balls may be dispensed into a bucket at a central location or by other means. Thus the launch point (i.e. driving bay) of every captured ball is known. The launch analysers measure the velocity vectors and preferably also the spin vectors of balls as they are hit and these measurements are then used to compute predicted flight and run of the balls (routine 71). Optionally, the system can then display the predicted flight and run of a ball before the run actually ends (routine 72) and thereafter display final information and score points after the run is complete. A decision routine 73 sorts predictions into those that have at least a small chance of "capture" (i.e. landing on a target and being recognised by a RFID reader) and those that do not. The outcome and "score" of a ball with virtually no chance of capture is displayed (routine 77) without further processing but this final display is preferably timed to

occur at the approximate end of the actual run for that ball. Prediction data for balls that appear to have some chance of capture are held in a register (routine 74) until such time that a matching code in a captured ball is obtained (routine 75) or until a timeout occurs (routine 76). The timeout may be separately calculated for each prediction and chosen to be a few seconds longer than the predicted time to capture. For captured balls, the final outcome with confirmation of landing on a target is displayed (routine 78).

In routine 79 the captured ball data is analysed to quantify errors and apply adaptive correction. Routine 79 performs a similar function to routine 29 in Figure 2 but a significant difference in Figure 7 is that for a given target there are only two outcome values for each ball, namely it is either captured or not captured. However, there are preferably numerous targets distributed over the outfield. (Optionally, targets may be divided into different segments so that more than two outcomes are available.) In contrast, the actual data in routine 29 (Figure 2) can have an infinite variety of positions within each target. Nevertheless, the captured ball data and the almost-captured ball data (i.e. all balls predicted to be within range of a target) can be used to analyse range and direction errors and minimise systematic errors because the very large volume of data builds up an accurate picture of which predicted shots enter the target and which do not. The "capture zone" is similar to the "sink zone" for putted balls described in Tierney, D.E. and Coop, R.H. 1999, "A Bivariate Probability Model for Putting Proficiency", *Science and Golf III*, ed. A.J. Cochran and M.R. Farrally, pp. 387-389, United Kingdom: Human Kinetics. In the present invention, the capture zone is mainly dependent on ball horizontal velocity and direction but descent trajectory and backspin also affect the capture.

Figures 8(a) and 8(b) are a plan view and a side section view of an instrumented target that uses RFID reader apparatus to detect balls on the target. Balls hit from the driving bays travel in a general left to right direction in Figures 8(a) and 8(b). Most of the area of the instrumented target comprises a top sloping surface 80. A re-entrant channel or trench 81 borders the front lip of the sloping surface 80 such that balls landing on the surface roll into the trench 81 where their identifying codes are recorded by at least one RFID reader (not shown). More than one RFID reader may be provided or a distributed reader arrangement may be used such that balls rolling into the trench 81 are read very soon after they roll in. One or more down-pipes 82 lead from the trench to a collecting sump 83.

The trench is sloped to cause balls to roll into the down-pipe or down-pipes and constant or periodic water-flushing (not shown) may be employed to ensure that the trench 81 is kept clear and balls readily collect in the sump 83. To this end, it may be advantageous to use balls that are slightly less dense than water. A flag-pole sits in a regulation size golf hole 84 and a RFID reader (not shown) identifies any ball that enters this hole to record a "hole-in-one" shot. Floodlights (not shown) may be provided inside the re-entrant trench 81 to illuminate the sloping surface 80 and the flag-pole during night-time and other periods of low visibility.

Balls travel at various speed towards the target. In most cases, balls roll onto the target over the upper surface of the re-entrant trench 81 and up the top sloping surface 80 where they slow down and eventually either roll back to fall into the trench 81, or, occasionally, into the hole 84. In other cases, especially with a high pitch shot, the ball may land directly onto the top sloping surface 80 and roll forward

into the hole 84 or, more usually, roll part way up the slope and then roll back, into the trench 81. Other balls that approach at high speed will roll or bounce off the top sloping surface 80 and not be captured. The top sloping surface 80 has a tendency to slow down the run of a ball and return it so that it falls into the trench 81 and eventually into the sump 83. In other words, the target captures balls that would roll onto its surface and also some way beyond if it were flat. This is shown in Figure 8(a) where arrow 85 indicates one possible approach direction and dotted line 86 represents the boundary of the capture zone for all balls approaching the target in the direction of arrow 85 (the "capture zone" is the area where balls would come to rest if the target were completely flat with an unbroken surface). A different capture zone boundary will obtain for different directions of arrow 85. To a first approximation the shape and extent of the capture zone boundary 86 is dependent on just the horizontal velocity of the ball at landing and the amount by which the path of the ball is offset from the centre of the target. Both these parameters can be predicted accurately from launch analyser measurements. Secondary factors such as descent trajectory, backspin, variations in ground bounce and undulations in terrain will affect the shape and extent of the capture zone boundary but with a large volume of data an accurate knowledge of the boundary for each approach direction can be built up. By this means, the outcome of balls that do not get captured can be predicted accurately by interpolation of the results for captured balls at several instrumented target locations distributed over the outfield.

For balls that carry further than 50 metres or so, the spin-rate and spin-axis tilt of the ball at launch, as well as its linear velocity vectors, are critical to its eventual carry distance, carry deviation and flight

duration. In order to predict reliably where and when a ball lands on the outfield for reliably matching landing-data with launch-data, it is essential that the spin imparted on a ball at impact is measured as precisely as possible as well as launch angle and linear speed. This is especially the case at peak usage in large driving ranges when the likelihood of shots from different bays landing at nearly the same spot at the same time is most frequent. Ideally, the predicted-shot outcomes and actual-shot outcomes should match to accuracies that are equal to, or better than, a golfer can be reasonably expected to observe. This would then ensure that the matching process works with complete integrity and credibility no matter how many balls land on any given target in any time slot. It is thus an aim of the invention to provide apparatus that measures ball launch velocity and spin vectors to a very high degree of precision.

In Figures 9(a) and 9(b), a launch analyser 90 is positioned generally forward of the pre-impact position of a golf ball 91 and parallel but offset from the expected straight-ahead launch trajectory of the ball (shown by arrow 92). In practice, the launch trajectory will have elevation angle typically in the range 5 degrees (as in a low trajectory drive shot) to 30 degrees or more (as in a 9-iron shot) and may diverge from the straight-ahead direction by ±25 degrees or more in azimuth. The golf ball surface is provided with retro-reflective elements 93 comprising small dots of retro-reflective material. A plurality of detection planes emanate from upper slit-apertures 94 and lower slit-apertures 95. The detection planes contain beams of light that are focussed into thin sheets which traverse the path of the ball 91 during part of its initial few centimetres of flight (e.g. from 10 to 50 centimetres or so). Dotted lines 96 indicate the

vertical extent of one of the detection planes emanating from an upper slit-aperture 94, whereas dotted lines 97 indicate the vertical extent of one of the detection planes emanating from a lower slit-aperture 95. These detection planes are very thin (for example in the range 2 to 5 millimetres) measured transverse to the plane of the slit-aperture, with very small or zero divergence angles.

Figures 10(a) and 10(b) are more detailed views of a detection-plane arrangement in Figures 9(a) and 9(b). A TXRX pair 100 comprises a light emitter device (LED) 101 and light sensor 102. A cylindrical lens 103 and a slit-aperture 104 are arranged with the TXRX axis, the length axes of the lens, and the length axis of the slit-aperture parallel and coplanar. The TXRX pair 100 is disposed on the principal focal line of the cylindrical lens such that parallel rays (show as dashed lines 105 in Figure 10(b)) converge to a line focus on the TXRX axis. With this arrangement, the field of view of the sensor 102 and the irradiation field of the LED 101 coalesce to form a detection plane with nominally uniform thickness 106 equal to the width (for example, in the range 2 to 5 millimetres) of the slit-aperture and with angular extent 107 determined by the length of the slit-aperture and the distance of the TXRX pair behind the aperture. The detection plane formed by the arrangement of Figures 10(a) and 10(b) is parallel to the Y = 0 plane, but in general the launch analyser apparatus requires other detection planes that are rotated about the X and/or Z axes. In practice, it is difficult to ensure that the TXRX pair 100 is exactly placed on the principal focal line of the cylindrical lens 103. Small errors in positioning result in the detection plane either converging or diverging, so that the thickness reduces or increases slightly with increasing range. These variations can be accommodated in the data processing.

The detection plane arrangement of Figures 10(a) and 10(b) may be used in other applications where it is desirable to detect information from a moving object and from a distance. For example an arrangement of detection planes may be used to detect vehicle information provided as a retro-reflective dot code or bar code on the inside front windscreen of a vehicle (e.g. on a tax disc). Since the windscreen is kept clean to give the driver good visibility, the retro-reflective code is also kept visible and protected from weather and grime.

Figures 11(a) and 11(b) show a diagrammatic plan view and side view of a golf ball 110 in a first position **y1** just after impact and the same ball 110 in a second position **y2**, two milliseconds later passing through detection planes shown by dashed lines 114, 115, 116 and 117. The ball diameter is 42.7 millimetres and (purely for example) travels at 64 m/s so the distance between **y1** and **y2** is very nearly three ball diameters. The ball 110 has, by way of example, a regular octahedron dimple pattern and is provided with a spherically symmetric arrangement of eight retro-reflective elements comprising two elements 111 and 112 that are in most direct detection view of the lower slit-apertures 65 and six other elements 113, some of which are below the ball (Figure 11(a)) or behind the ball (Figure 11(b)). The retro-reflective elements 111 through 113 are positioned on the centres of each facet of the octahedron. The eight elements thus form the corners of a hypothetical cube with sides 24.6 millimetres square, and this provides a simple model of their relative spatial positions and orientations.

Retro-reflective material has significant thickness because the light-reflecting surfaces of it are arranged in a three-dimensional shape, such as a prism. For example, a preferred high-grade retro-reflective material

is 0.4 millimetres thick. However, golf-ball dimples are typically only 0.2 millimetres deep so attaching reflecting material of this kind to a golf ball has an unbalancing effect on its aerodynamic properties unless a suitable number of reflectors are arranged to be part of the spherically symmetric dimple pattern of the ball.

Typically, each retro-reflective element is inserted as a separate element within the area of one large dimple on the ball surface. These elements may be small circular discs of micro-prism retro-reflective material, or may be single corner-cube prisms, "cat's eye" lenses or the like. Alternatively, retro-reflective elements may be directly fabricated or painted on the surface of a golf ball and individual areas may occupy more than one dimple.

It is necessary that the means of attachment of the elements to the golf ball surface is robust and withstands the high impact forces and significant ball deformation during a golf shot as well as the cleaning and scrubbing operations after collection from the outfield. A large measure of protection can be afforded by having the retro-reflective element recessed slightly below the outermost surface of a golf ball (as in a dimple). Acrylic corner-cube reflectors with a glass layer or other scratch-resistant surface may be used. In one preferred construction the retro-reflective part has a tough, scratch resistant protective surface and is ruggedly attached onto a short cylindrical pellet that is inserted into cylindrical cavities formed in the ball during moulding, and is slightly recessed. The depth of the pellet may extend beyond a thin outer casing (which is often about 2 millimetres thick in a two-piece ball construction) and into the inner rubber core. Thus, the pellet is encased in a resilient and protective housing and may be prevented from dislodging by barbs on the

pellet surface and/or adhesive bonding. The entire surface of the ball may be encased in a transparent outer cover.

The retro-reflective elements provide suitable reference marks from which the spin rate and spin axis as well as the linear velocity components of the ball can be detected. Advantageously, this arrangement can be used to measure the velocity and spin components of the ball with any arbitrary initial orientation prior to impact. Not only is the spin rate and spin axis orientation measured, but the orientation of the octahedron dimple pattern relative to the spin axis can be determined, which can provide superior characterisation in a ball flight prediction model. The spin and velocity measurement means may employ high speed, time-elapsed camera images, but preferably the measurement is provided using an array of detection planes. In alternative arrangements, six retro-reflective elements may be positioned on the vertices of an octahedron pattern or twelve such elements on the facets of a dodecahedron and so on. The methods described above can be adapted for spot-kicks on a soccer or rugby ball to measure the resultant velocity and spin components. In this case the widths of the slit-apertures could be larger than those required for golf-ball measurements.

A significant advantage of providing a ball with retro-reflective parts on its surface is that it can be much more visible as it flies through the air during night-time or other periods of low ambient lighting. The higher visibility is provided by illumination from flood-lights mounted near each bay, which also illuminate the distance targets 41 to 45. As a ball flies down range, the observation angle (i.e. the angle subtended at the golf ball between the golfer's eyes and the local light source) gradually decreases, and consequently the

reflectivity increases and partly compensates for the weaker illumination at greater range. The visibility can be increased by providing more of the surface of the ball with retro-reflective surface. For example, instead of one retro-reflective dot on each facet of a ball there may be a symmetrical arrangement of more than one, e.g. three in the centre of a triangular facet.

Preferably, each bay is fitted with a separate relatively low-power flood light positioned just above head-height but forward of the golfer so that there is ample head-room above and around the golfer to swing a driver or other club. This construction minimises the said observation angle, especially for balls with steep trajectories, and so enhances reflectivity off the ball. With this arrangement and judicious use of side-lighting and/or ground mounted lights, the total lighting power requirements can be significantly reduced compared to a driving range using standard golf balls and non-reflecting targets. This in turn minimises glare, sky glow and other light pollution problems as well as saving energy.

The ball of Figures 11(a) and 11(b) may be used in combination with portable apparatus adapted to assist location of the ball on a golf course.

The ball passes through the four detection planes 114, 115, 116 and 117, which all emanate from lower slit-apertures 65 so the associated light sensors detect the reflections of associated light emissions off the side of the golf ball 110. Other detection planes (not shown) emanate from upper slit-apertures 94 and from other lower slit-apertures. The detection planes that emanate from upper slit-apertures sense reflections from a different angle, directed downwards by typically 40 to 60 degrees. Also, detection planes emanating from either upper or

lower slit-apertures (94 and/or 95) may be rotated about the Z-axis so as to be partly directed forwards or backwards along the Y-axis. Thus, as it passes through a plurality of detection planes, the ball and the retro-reflective elements thereon are detected from a multiplicity of angles and at various intervals along its initial trajectory so that plentiful data are available from which the velocity and spin vectors of the ball can be accurately computed.

Figure 12 shows the time dependant voltage signals **Va**, **Vb**, **Vc** and **Vd** corresponding to the golf ball 110 passing through detection planes 114, 115, 116 and 117 respectively. The four voltage waveforms each contain two pulses 121 and 122, of short duration and high amplitude which correspond to the passage of the two retro-reflective elements 111 and 112 respectively through detection planes 114 to 117. For simplicity, we ignore the presence of the other six elements, some of which may be marginally within detection view. In addition to pulses 121 and 122, each waveform also shows a subsidiary pulse 123 of lower amplitude and longer duration coincident with both 121 and 122 and corresponding to the slower amplitude rise and fall of sensor signals due to reflection off the ball surface as it enters and exits each detection plane in turn. By analysing the voltage signals the four instants in time **t1**, **t2**, **t3** and **t4** when the ball passed through detection planes 114, 115, 116 and 117 respectively, can be determined.

Detection planes 114 and 117 are vertical and normal to the azimuth direction of the ball. The ball velocity **Vy** parallel to the Y-axis is given by the distance between detection planes 114 and 117 divided by (**t4** - **t1**). Detection plane 115 is also vertical but is rotated about the Z-axis as shown. Consequently the displacement **δx**

(see Figure 11) is equal to **Vy** x (**t2** - **t1**) / tanθ; where θ is the angle of inclination between detection planes 114 and 115. Thus, the XY co-ordinates of the ball and the retro-reflective elements can be found from analysis of the time delay between corresponding signals. Similarly, the elevation angle of the ball is obtained from time delay (**t4** - **t3**), its speed and the geometry of detection planes 116 and 117.

In the arrangement of Figure 11 the reflector pattern repeats every 90 degrees so care is required to ensure that high spin rates are accurately recorded by providing suitable spacing between at least two detection planes. Low elevation angle shots (i.e. drives) tend to have low spin rates whereas high elevation angle shots (i.e. pitching irons) have high spin rates; where spin rate is defined as the ratio of the peripheral speed due to spin of the ball divided by its linear or translational velocity. Thus, it is advantageous to provide at least two detection planes with small separation distance for high elevation angles and larger separation distance for low elevation angles and this is provided by detection planes 116 and 117.

The qualitative features of the signal waveforms of Figure 12 are evident, but it is not so obvious how to extract precise data from such waveforms. The preferred method is to use a guess of the motion of the ball and the retro-reflective elements and apply this to a mathematical model of the array of detection planes and their response to reflections from a ball and from those retro-reflective elements that are detectable by the detection planes. The main features of the waveforms allow an initial approximate guess of the ball velocity, trajectory and spin from which model data are generated. The model data and real data are compared and the differences are used to obtain an improved guess (i.e. an

improved estimate). We repeat this process until the model data converges to nearly the same as the real data. The above is a simplified description of non-linear minimisation or non-linear estimation which are well-known techniques in engineering. One preferred mathematical technique for solving the estimation is the Levenberg-Marquardt method. In Figure 12, the waveforms are shown as continuous traces, but in practice it is preferable that the TXRX pairs are operated in pulse-multiplexed mode and the data is acquired as a sequence of digital samples (from a sampling analogue-to-digital converter), which are then used as input data in a mathematical model of the detection planes array and probable ball launch parameters. A non-linear estimation such as the Levenberg-Marquardt method then extracts accurate estimations of the true launch velocity and spin vectors of the ball.

Figure 13 is the plan view of an alternative ball launch analyser where the velocity vectors and certain orientations and positions of a club head 130 are sensed prior to impact with a golf ball 131 and only the velocity vectors of the ball are sensed. A sensor enclosure 132 has a detection plane window face 133 generally parallel but offset from the golf swing and ball trajectory paths and provides a number of detection planes 134 crossing the path of the club head and golf ball in the pre-impact and post impact region of a golf shot. The detection planes comprise a mixture of normal, angled, narrow width and expanded width types to fully detect the approach direction (in azimuth and elevation), speed, dynamic loft and offset (in vertical and horizontal sense) of the club head 130 and the launch velocity vectors of the ball. This gives sufficient data to determine the spin vectors of the ball as well as its velocity vectors. From this, a prediction of the subsequent ball flight can be made. Errors in

measurement will degrade the accuracy of the flight prediction, but these errors are mainly systematic, especially if known types of club and a known type of ball are used. It is thus possible to correct systematic errors by applying feedback of the actual flight outcome measured by accurate means.

Figure 14 shows a side view of the club head 130 and ball 131 as "seen" by the detection plane array. The motion of the club head is sensed by tracking three retro-reflective elements in the form of small, circular, retro-reflective dots, 141, 142 and 143 attached to the club head. The positions of the centre-planes of three detection planes are shown by dotted lines 144, 145 and 146, where the planes are normal to the page in Figure 14. The diameter of the retro-reflective dots are preferably nearly the same as the width of the detection planes so that the signal pulse generated when a retro-reflective dot passes through a detection plane has a well defined peak. By this means the point in time when the dot is exactly central in a detection plane can be accurately estimated. The diameter of the retro-reflective dots may however be larger or smaller than the detection plane widths. Larger dots give higher signal magnitude but have flatter peak waveforms (though good estimation of the centre of the peak is still possible) and can be less convenient to attach to the club head.

The contrast of the retro-reflective elements 141, 142 and 143 against reflections from the body of the club head can be enhanced by using filters to polarize the transmitted light from each TXRX pair in one direction and a second filter (for each TXRX pair) to polarize the received light at 90 degrees to the emitted light. In one possible arrangement, the ambient signal amplitude is measured just before and/or just after a (pulsed) light emission and the reflected plus ambient signal amplitude

is measured during the TXRX pulsed emission. Since these two measurements (or three measurements in the case of measurement before and after the pulsed emission) occur at nearly the same time so the club head position and orientation change very little during these measurements, the amplitude response to light reflected exclusively from the retro-reflective elements can be found very precisely (assuming the above polarising filtering arrangement removes most of the unwanted reflections). In general, it is preferred to use infrared TXRX pairs as these generate light outside the visible spectrum, but other light wavelengths such as visible red light may be preferable since some polarising filters are more readily available at these wavelengths. If necessary, a mixture of light wavelengths can be used to eliminate visible disturbance prior to impact and enhance performance during the impact phase only. Also, the club head body can be sprayed with non-reflective coating prior to attaching its retro-reflective element.

Figure 15 shows the time dependant amplitude waveforms of the three retro-reflective elements of Figure 14 as they pass through the three detection planes. The three waveforms each contain three pulses. In waveform 151, consecutive pulses 152, 153 and 154 correspond to the passage of the retro-reflective dots 141, 142 and 143 respectively through detection plane 144. In waveform 155, consecutive pulses 156, 157 and 158 correspond to the passage of the dots 141, 142 and 143 respectively through detection plane 145. Detection planes 144 and 145 are parallel and it can be seen that waveform 155 is a time-delayed replica of waveform 151. The speed of the club head can be found from the duration of the time delay and the distance between detection planes 144 and 145. In waveform 159, pulses 201, 202 and 203 correspond to the passage of the dots 141, 142 and 143 respectively through detection plane 146, but in this case pulse 202

precedes pulse 201 because, due to the inclination of detection plane 146 from the vertical, retro-reflective dot 142 is the first to pass through.

In Figure 15, the waveforms are shown as continuous traces, but in practice it is preferable that the TXRX pairs are operated in pulse-multiplexed mode and the data is acquired as a sequence of digital samples (from a sampling analogue-to-digital converter). In one preferred but not limiting method of data analysis, the true centres of the pulses on the time axis are found by quadratic interpolation of three data points nearest each apparent peak to yield nine precise points in time (in the example of Figures 14 and 15), which are then used as input data in a mathematical model of the detection planes array and club head motion. A non-linear estimation such as the Levenberg-Marquardt method then extracts accurate swing parameters of the club head.

In purpose-built clubs, the retro-reflective dots 141, 142 and 143 are preferably inserted into shallow circular recesses that are formed at manufacture. The exact location of the centres of the retro-reflective elements relative to the club-face are then known very accurately. It is also desirable to provide a similar retro-reflective arrangement on other makes of golf clubs. For example, retro-reflective dots 142 and 143 can be provided on a single strip of self-adhesive sticker, which is attached to the toe of the club head with the edge of the sticker aligned with the edge of the club-face as shown. This ensures that the centres of dots 142 and 143 are on a line parallel to the loft angle of the club-face. The self-adhesive sticker preferably forms a low reflectivity substrate to enhance the contrast of the retro-reflective dots. The dot 141 can also be mounted on a low reflectivity sticker; the position of dot 141 is less critical as its chief purpose is to provide an

approximate indication of lie angle (i.e. the amount by which the heel-toe axis tilts relative to the horizontal). The retro-reflective dots are typically all the same nominal size, but a mixture of different sizes can be used to provide a code to differentiate between different club-head characteristics. For wood clubs, a preferred position of retro-reflector dots 142 and 143 are on the centre of the crown (i.e. the top surface of the club-head) and aligned front to back (substantially along the Y-axis). As these crown-mounted dots face upwards they need to be detected by a downwardly-oriented detection plane such as detection plane 96 in Figure 9(b).